Optical Density Analysis of X-rays Utilizing Calibration Tooling to Estimate Thicknesses of Materials/Parts

Presented by: David Grau
04/18/08

[redacted]

[redacted]

Contents

Objective

- To provide background and details on the use of a technique for estimating thickness variations in materials.

Background

Industry Background

- Throughout the non destructive test (NDT) community several techniques have been developed over many years to determine the thickness of materials/parts. The vast majority of techniques require tedious testing of a part to verify thicknesses meet certain thickness requirements. In addition, in the case that a part does not meet a drawing thickness requirement or is suspect to not meet a drawing requirement the part must be analyzed to rationalize its use. At this point a definitive range for the thickness of the part must be obtained. In most cases this requires tedious part testing.
- In addition to the above, most NDT methods are restricted in their coverage area by the tooling they employ. Therefore, for certain configurations (i.e. in joints or adjacent to welds) complete coverage of the part by the NDT equipment may not be possible.
- Although it is well known that the thicknesses of parts can be derived from detailed testing and that in general variations in part thicknesses can be witnessed in x-rays of the parts, what is not clearly understood in industry is how to determinately quantify a part's thickness or a change in a parts thickness using an x-ray.
- One of the main constraints with quantitatively assessing thickness variation from an x-ray is the fact that the relationship between x-ray density and thickness is non-linear.
- Furthermore, depending on a parts thickness and the exposure settings of the x-ray, the intercept of the density to thickness graph is undefined.

Background at NASA/ULA

- Due to a need for a new NDT technique a joint effort between NASA and Boeing/ULA was launched to developed a technique to assess a part's thickness change utilizing a combination of x-rays and part configurations.
- Originally, only a single tank configuration needed to be examined and utilizing the expertise of the ULA/Boeing LIII (Rick Eckelman) and the NASA expert in digitization (William Winfree) a means of quantitatively assessing changes in thickness from x-rays was developed.
- This technique was however limited in use to only a certain configuration of parts and was found tedious to use with differing parts, differing configurations, differing materials, and at different x-ray exposure properties.
- Further work was conducted by Boeing/ULA/NASA to develop a thickness change estimation technique that could be used on a global level for all parts, all materials, and all configurations.
- Boeing/ULA LIII Rick Eckelman did develop a means of estimating thickness from an x-ray on a global level, however the technique that Boeing/ULA developed was determined to not be scientifically based nor could it be proven without significant research.
- At that point the NASA-KSC began working independently to develop an alternative technique to those previously invented.
- The problem was defined as the need to develop a technique to assess a material's thickness variations based solely on the use of a digitized version of a part's x-ray and x-ray analyzing software.

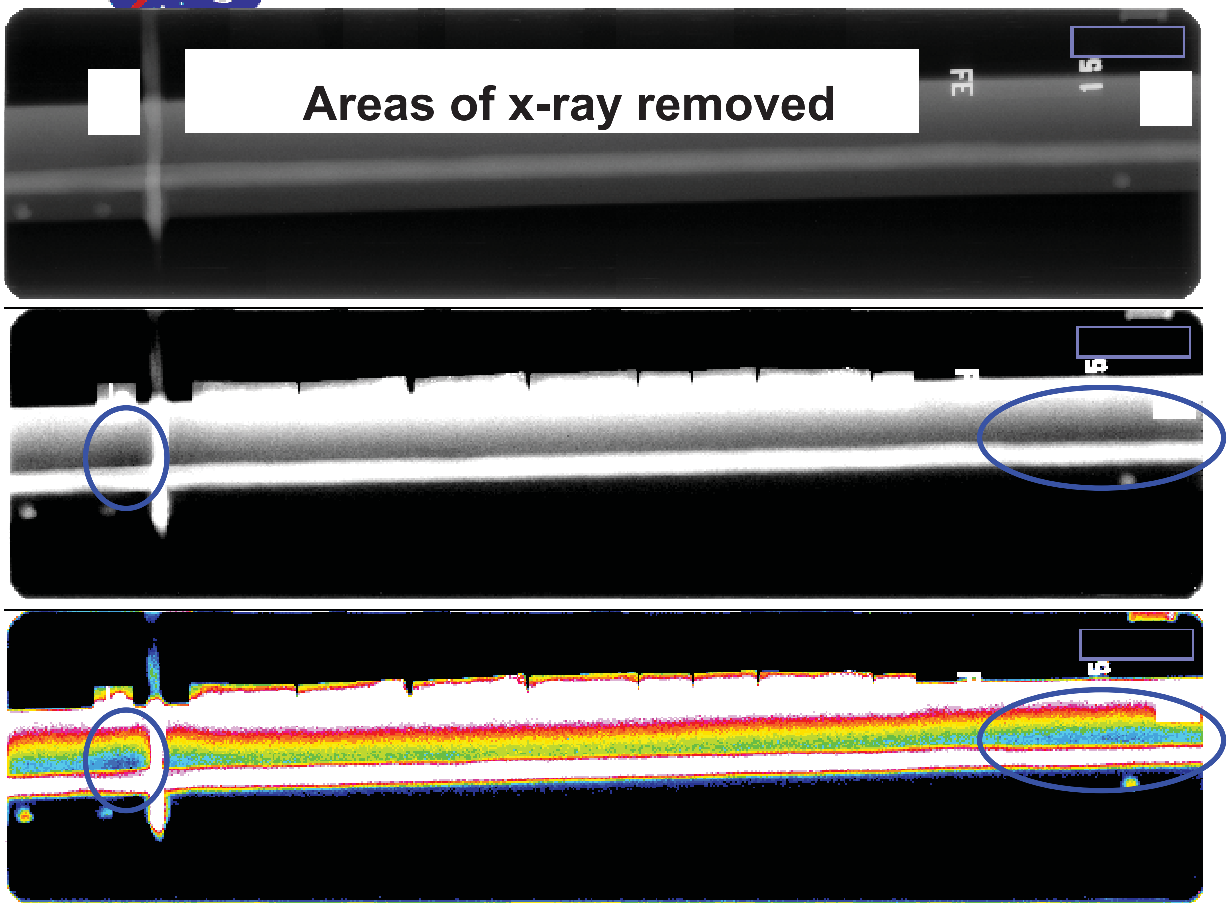
X-ray Basics

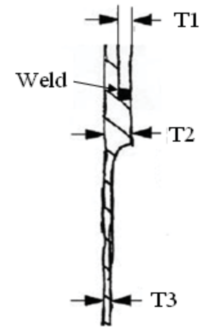
X-ray Basics

- Prior to continuing with the discussion at hand some basic principles of x-rays needs to be explained.
- An x-ray can be thought of as a picture (photo) representation of a parts internal volume.
- In general, for an x-ray the longer a film is exposed to x-rays the denser/darker the film will become (Density in the above sense is a measure of x-ray darkness not a materials volumetric mass).
- Depending on the time of exposure of a part/material to x-rays, the thickness and density (volumetric mass) of a material, and the capturing of those x-rays on x-ray film the density (darkness) of the x-ray may vary throughout the developed x-ray film.
- For homogeneous materials any density/gray changes witnessed within an x-ray will typically represent thickness variations since for the thinner regions of the material more x-rays will penetrate through to the x-ray film.
- For non-homogeneous materials/parts imperfections within a parts volume or variations in a parts/materials density may be apparent in it’s x-ray due to variations in the x-ray’s density/grayscale, i.e. since more or less x-rays may penetrate through the part to the x-ray film.

Problem Identification

Problem Identification





X-ray with viewable range stretched

X-ray with viewable range stretched and with 16 colors used in place of grays.

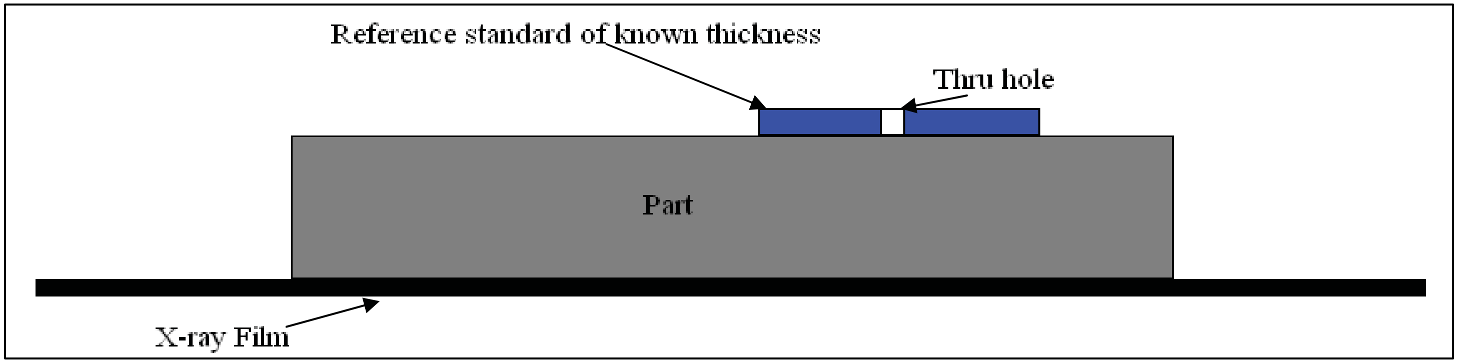
Regions of a part with local thickness variation can be identified as a change in density/grayscale within the x-ray. By stretching an x-ray's viewable range of grayscale and/or by altering the color scheme of a digital x-ray, variation in an x-ray's grayscale can be identified more readily. <u>In general, variations in an x-ray's grayscale indicate variations in a parts material density, thickness, or both.</u> The question becomes, if parts are composed of homogenous materials how do we quantify a level of thickness variation from a variation in x-ray density for parts of varying thicknesses x-rayed at various exposure settings?

Solution Description

Solution Description

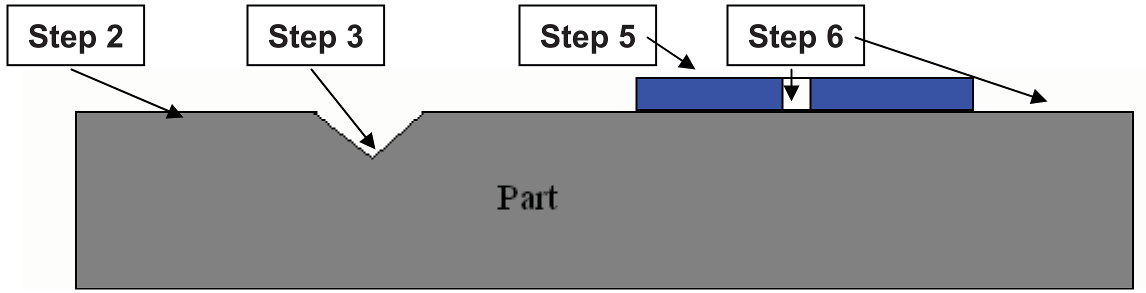
- After several months of research a technique was developed utilizing the data analysis tools available for x-ray analysis and the existing digitized x-rays.
- At that time the technique developed utilized the image quality indicators (that are required to analyze welds) as reference standards within each digitized x-ray to derive a linear correlation for x-ray density to thickness.
- Based on x-ray theory and the existing x-ray data available the shape of the x-rays characteristic curves suggested that a reference standard with known thickness could be used to derive a conservative thickness variation assessment.
- The technique was later proven utilizing a limited number of x-rays containing multiple image quality indicators.
- The following is a description of the test article set-up and technique in practical application.

Solution Description
Test Article



- Basic Tooling Set-Up for X-ray/Analysis
  - The actual lay up of materials prior to x-ray exposure is quite simple.
    1. The test article/part is to be place atop the raw x-ray ensuring the region of interest is aligned for proper and aligned perpendicular x-ray exposure capture.
    2. One or multiple machined referenced standards of like material/density with known thicknesses are to be placed atop the part (preferably in a region of nominal and non-varying thickness) such that the exposure of the combined part and machined component (tool 2) lay-up is captured on the x-ray.
    3. Depending on the accuracy of thickness estimation required the lay-up must be exposed such that the regions of the x-ray to be analyzed have a density range between 1 and 4.5.
  - After the exposure of the tooling to the x-ray process the exposed x-ray must be digitized using adequate technology.
  - The digital image can then be analyzed using an image analysis software package and the techniques described in this package.
- Please note, this is one test set-up that can be used for this method, several test configurations exist.

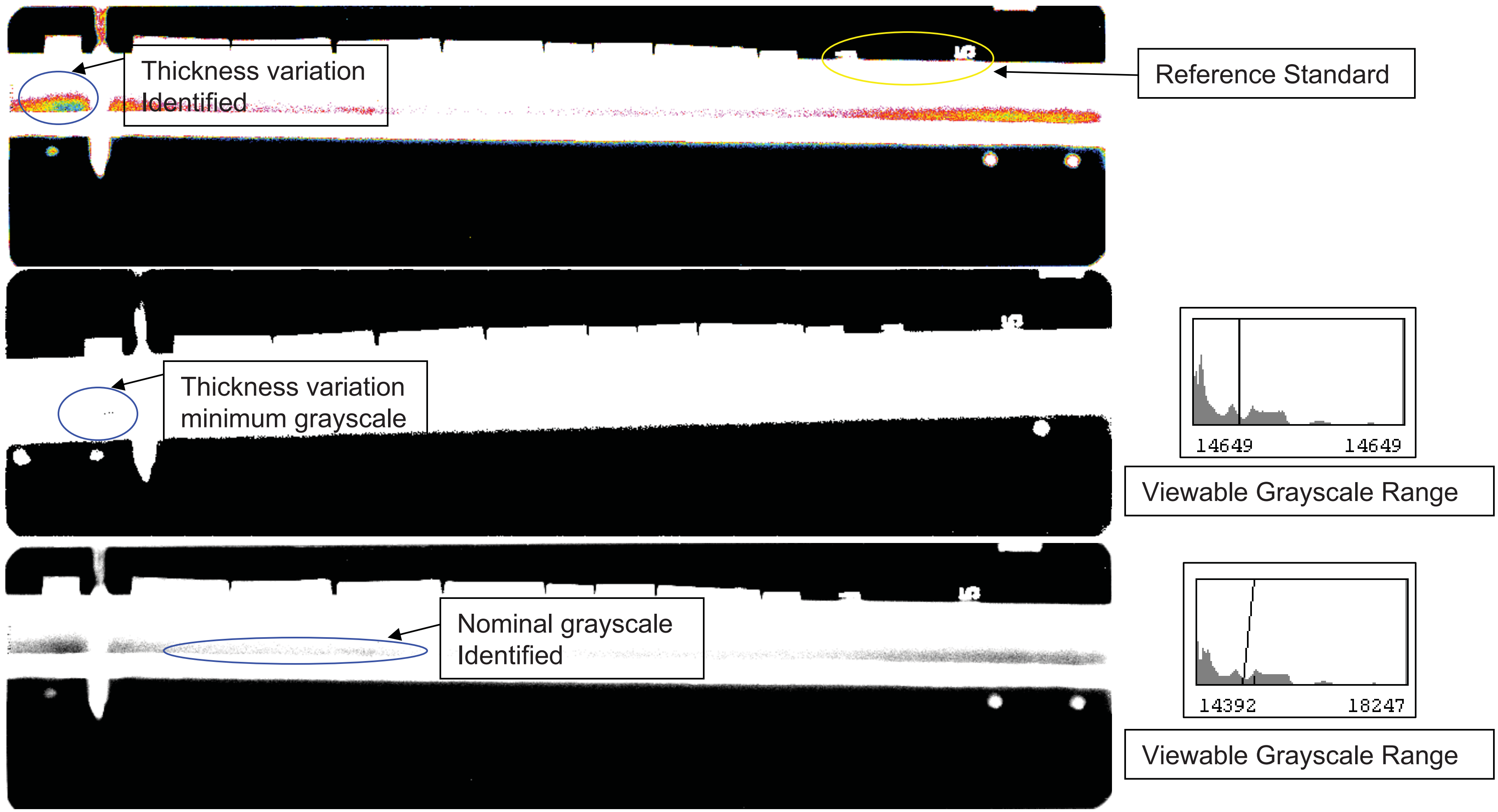
Solution Description Procedure



- Basic Solution Methodology
  - (1) Utilizing a digital x-ray image and image analysis software adjust the digital x-ray image to ensure all pixels are displayed in grayscale (for a 16 bit image this would correlate to a full scale of 2^{16} or 65536 possible grayscale values). In addition, utilizing the reference standard calibrate length and width.
  - (2) Determine the grayscale value of the part in a region that has an assumed nominal thickness (or a known thickness for absolute thickness estimation). This will serve as the reference thickness to calculate all other thicknesses above or below this.
  - (3) Determined the grayscale value of an area of the part that is of interest, i.e. region with thinning or material thickness variation (on a more global scale one could determine all grayscale values within x-ray and apply step (8) globally).
  - (4) Determined the change in grayscale from the area of interest to that of the nominal/reference region. This change in grayscale correlates to a change in thickness from the reference region to the region of interest.
  - (5) Determine the grayscale of the thru thickness of the reference standard. This grayscale is comparable to the sum of the part thickness under the machined component and the machined components (tool 3) thickness.
  - (6) Determined the grayscale of the region of the reference standard within the thru hole (or used value in step 2 if accurate). This grayscale is comparable to the thicknesses of the part under the machined component.
  - (7) Determine the grayscale change related to the thickness of the machined component by subtracting the value determined in (6) from the value determined in (5). This value of grayscale directly correlates to the thickness of the machined component. This is essentially a calibration for change in grayscale to change in thickness.
  - (8) Using the numeric correlation of thickness to grayscale realized in step (7) determine the variation of thickness in the part by dividing the value obtained in step (4) by the value obtained in step (6) and multiplying the ratio by the thickness of the machined component (tool 3).
  - With sufficient process control, utilizing the above technique the user of this method can estimate the changes in thickness of a part from a reference region. Furthermore, if the thickness of the reference region is known the entire parts thickness/contours can be estimated if the parts geometry is thoroughly understood and the x-rays characteristic curve is understood.

Practical Application

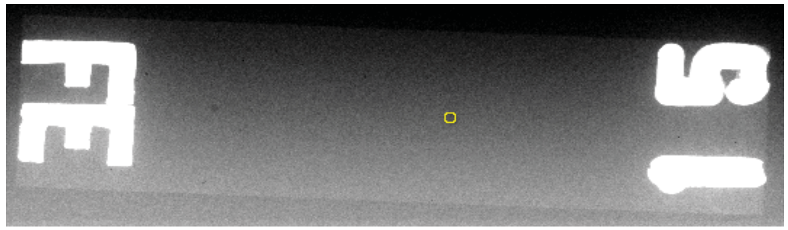
Estimating Grayscale Change



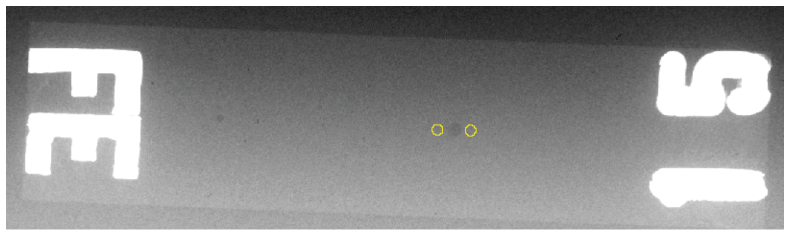
In this x-ray example we identify the minimum grayscale level of an area with thickness variation (14649). After the minimum grayscale in the area of thickness variation is identified the assumed nominal thickness of the part is identified (18247). Finally, the variation between nominal and maximum thinned area is computed (3882).

Reference Standard Usage to Calibrate

1



2



Results

File Edit Font

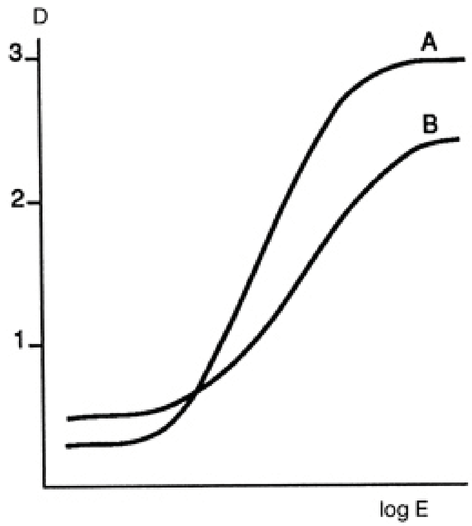
	Area	Mean	Min	Max
1	0.0007	24751.8588	23901	25443
2	0.0013	25482.9294	24672	26471

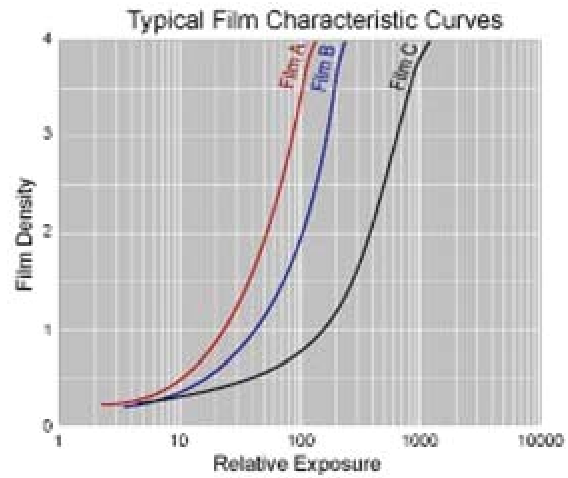
Utilizing a reference standard within the x-ray's field of view (Note: this standard is not the standard from the previous slide, it is only used for demonstration purposes) relationship between thickness and grayscale at a level of ~25000 grayscale points can be estimated at 0.003" per 731 grayscale points.

However, due to the fact that the grayscale to thickness relationship is non-linear within an x-ray, the above relationship cannot be considered accurate for the entire grayscale range within an x-ray's field of view. Based on the characteristic curve of the x-rays being used, the thickness to grayscale relationship can be used to estimate thicknesses of regions with grayscales under 24751.

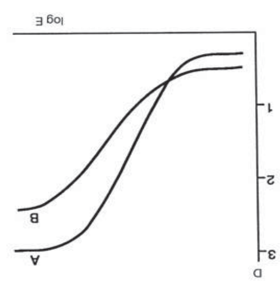
Characteristic Curve

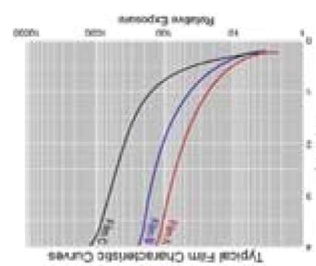
X-ray Characteristic Curves



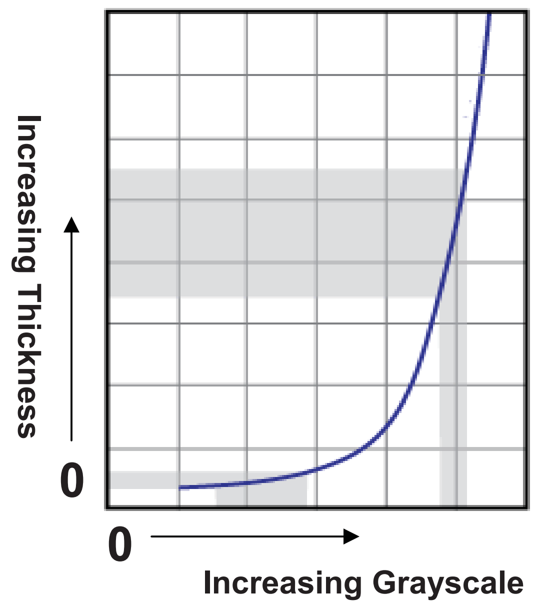


- The relationship between exposure/thickness and density/grayscale is governed by the x-ray and x-ray process.
- The above curves represent the characteristic density to exposure relationships that x-rays are governed by.
- The lower the density the lighter/more transparent the exposed x-ray film becomes.
- For our examples the lower the density the higher the grayscale and the thicker the part.
- From the curves we can see that once a density of ~1.0-1.5 is reached the slope of the curve begins to decrease.
- Since high density equates to low grayscale on an actual exposure and since the higher exposure equates to lower thickness the axis for these plots must be readjusted when comparing grayscale to thickness (Below and next page).



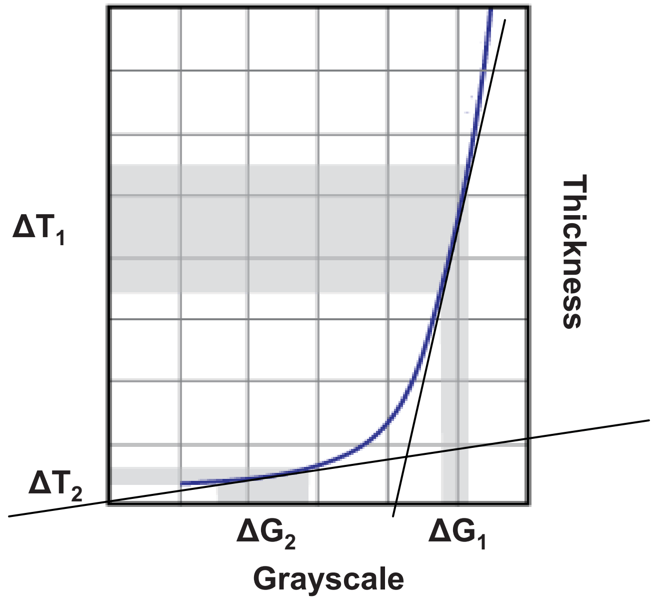


X-ray Characteristic Curves



- In the above plot the characteristic curve for an x-ray is expressed in grayscale and thickness instead of the traditional Density and Exposure
- We can see that the shape of an x-ray's Thickness to Grayscale plot (Exposure to Density) is parabolic at lower grayscales (prior to Density dropping below ~1.0 – ~1.5).
- Therefore, utilizing a reference standard atop a part (i.e. with a sum of thickness/grayscale greater than that of the thickness of the region in question) will result in an accurate or conservative thickness variation estimate.
- Furthermore, utilizing multiple reference standards made of a part's material with comparable thicknesses (or a wedge of known slope) in the field of view of an x-ray a precise calculation of thickness variation can be realized.

X-ray Characteristic Curves



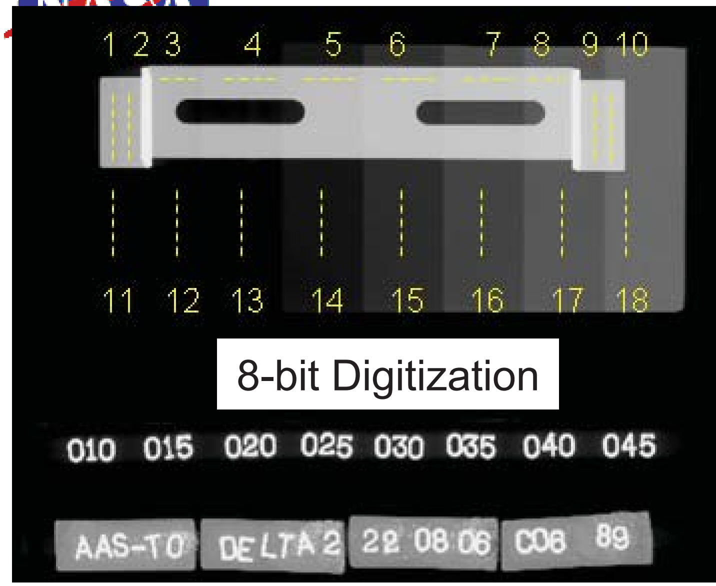
$$\boxed{\frac{\Delta T_1}{\Delta G_1} > \frac{\Delta T_2}{\Delta G_2}}$$

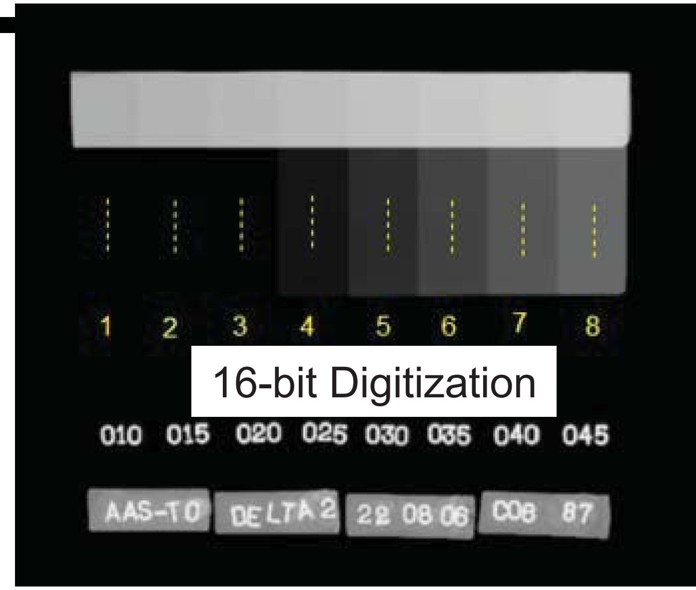
$$\boxed{\frac{\Delta T_1 \Delta G_2}{\Delta G_1} > \Delta T_2}$$

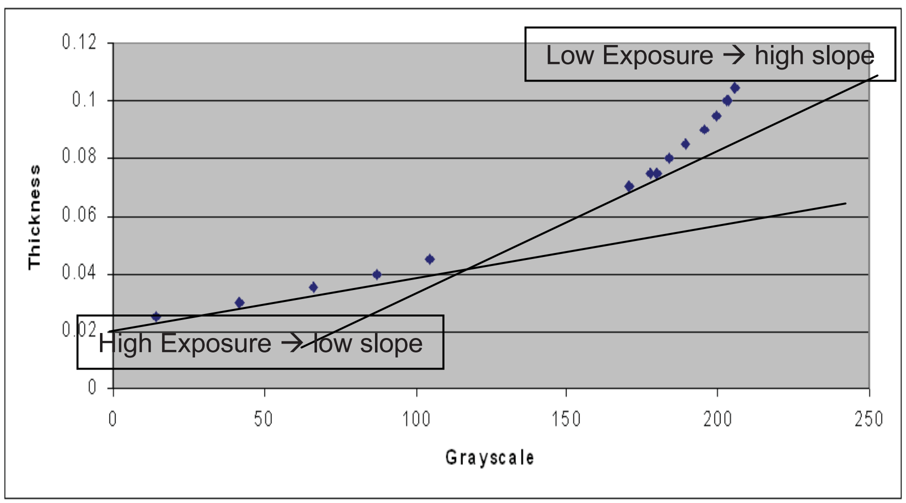
- As was explained on the previous page if the slope of a tangent line drawn using two points on the right side of a characteristic curve (fit a T to G curve) is calculated and compared to the slope of a tangent line drawn using two points on the left side of the same characteristic curve the slope of the tangent line to the right side of the characteristic curve will always be greater than the slope of the tangent line drawn on the left side of the characteristic curve (assuming a parabolic and not an S-shaped curve).
- Therefore, utilizing a reference standard on top of a part (or adjacent to a part) with a total relative thickness above a region of interest, utilizing the properties of the characteristic curve a thickness change can be estimated that is considered conservative.
- Furthermore, with proper use of the characteristic curve and reference standards, a materials thickness variation can be accurately quantified.

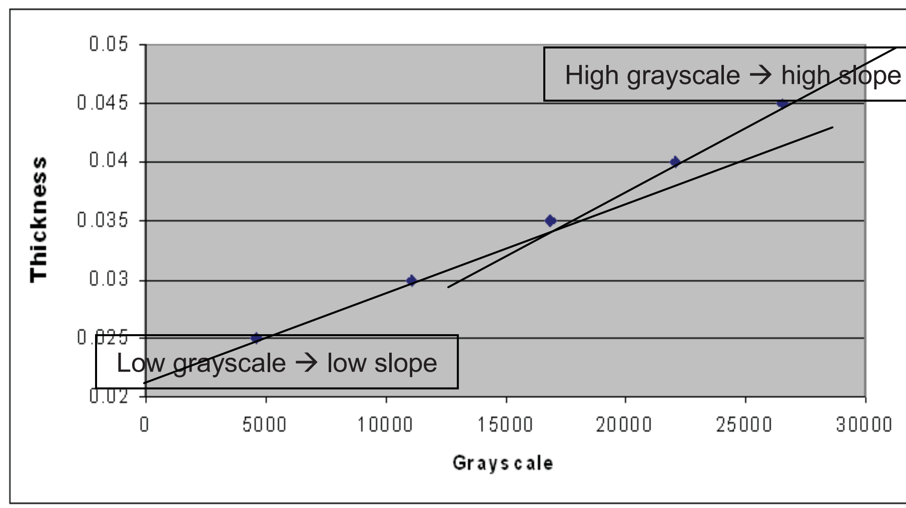
Characteristic Curve Practical Data

Characteristic Curve Identified in Practice





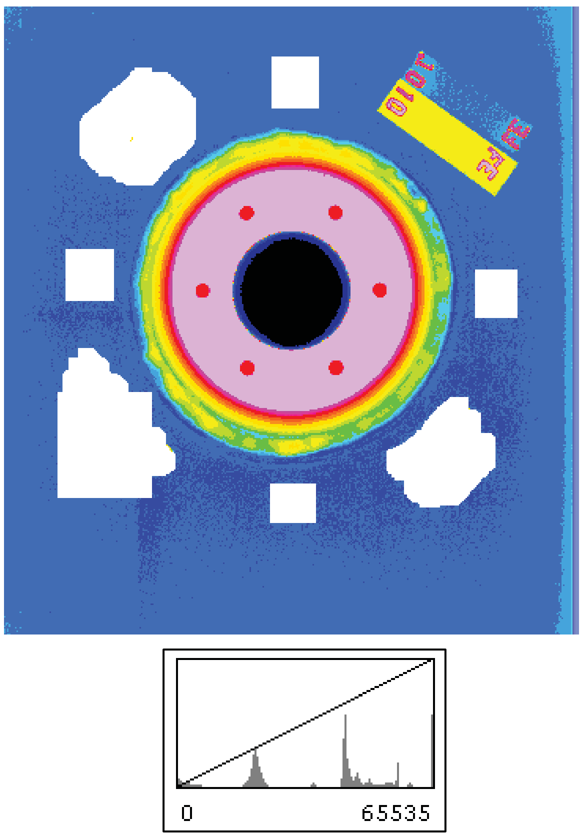


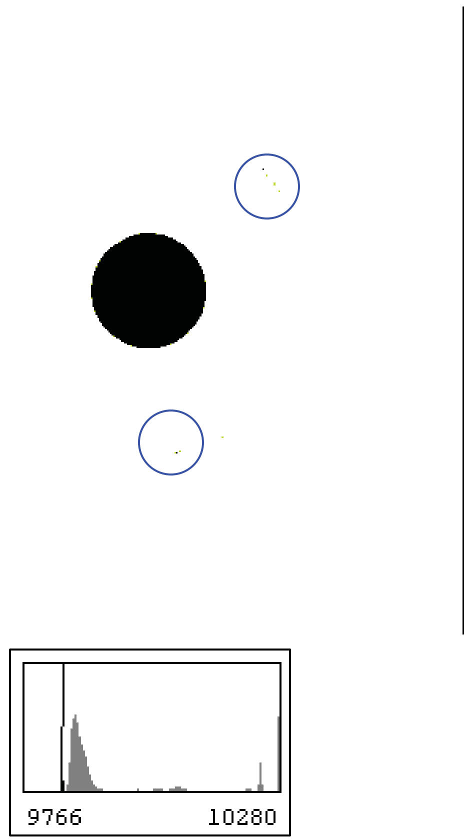


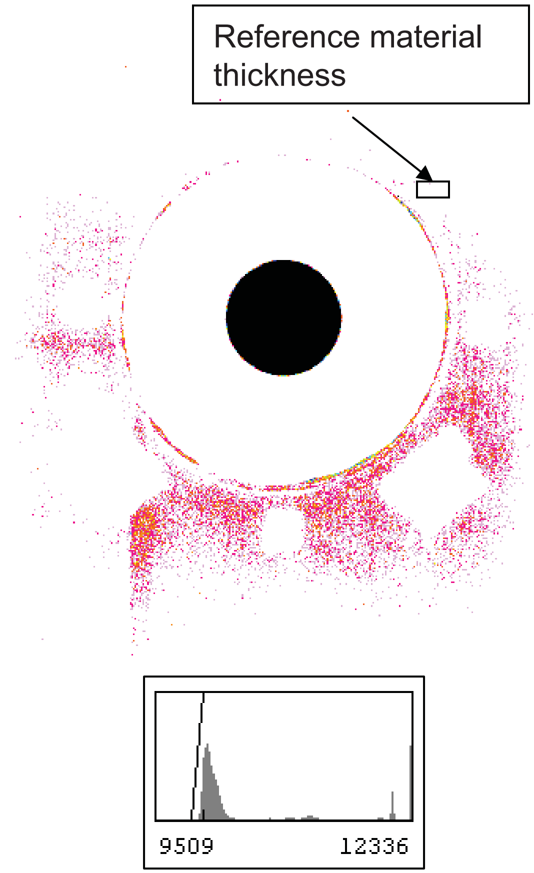
The above two examples illustrate the shape of an x-rays characteristic curve. The part(s) used above are Stainless Steel machined with varying levels of thickness and/or a Stainless Steel shim.

Example

Example





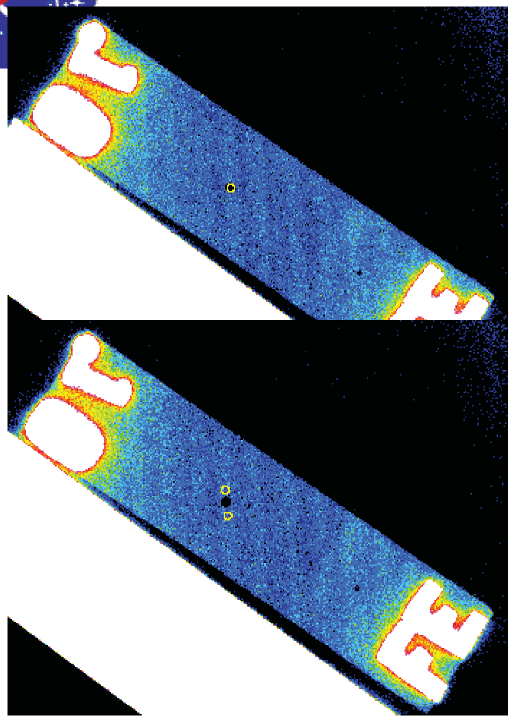


First observable points of undercut/thinning occur at ~9766 grayscale.

Nominal grayscale of region adjacent to worst case undercut is ~12336.

The maximum change in grayscale for undercut adjacent to this weld was estimated at 2570 points from the reference material grayscale.

FM-21 Inspection Data, Review, and Acceptance
4M Oxidizer Side Boss

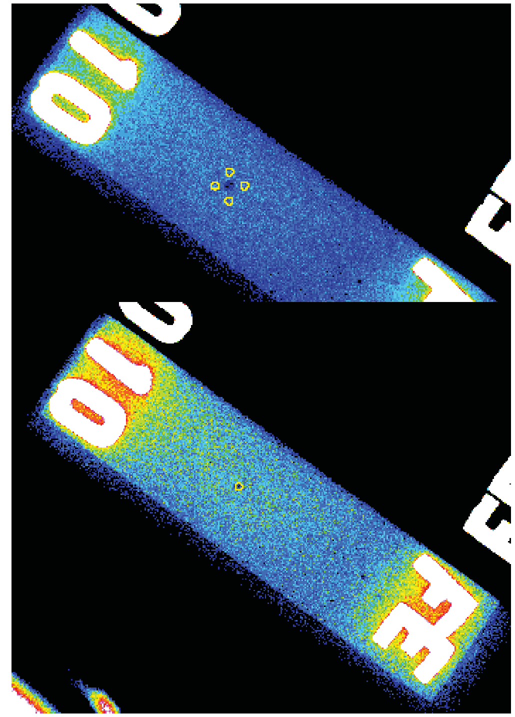


Results

File Edit Font

	Area	Mean	Min	Max
1	0.2258	14437.0113	13364	15420
2	0.4515	15997.8870	15163	16705

Utilizing the reference standard placed directly on the part, the relationship of thickness to grayscale is estimated at 0.002” per 1561 grayscale points.



Results

File Edit Font

	Area	Mean	Min	Max
1	0.2258	34259.4068	33410	35466
2	0.9031	35072.8771	33924	35980

Utilizing the reference standard placed on a shim on the part, the relationship of thickness to grayscale is estimated at 0.002” per 813 grayscale points.

The effects of the characteristic curve can be seen here. At a level of ~35000 grayscale points the slope of the characteristic curve is very steep at 0.002” per 813 points. At a level of ~15000 grayscale points the slope of the characteristic curve is almost half that of the slope at 35000.

Example

- Based on the previous plots the maximum grayscale change from assumed nominal was estimated at ~2570 points at a grayscale level of ~15K.
- From the penetrameter the relationship for change in Grayscale to Thickness at a grayscale level of 15K was estimated at ~1500 points for ~0.002” (or 750 points per 0.001”).
- The estimated thickness variation for this examples area of interest would be ~0.0034” through use of the reference standard within the field of view.
- Therefore, the resulting thickness for the area of interest would then be the thickness of the reference region minus 0.0034”.

Other Considerations

Other Considerations

- Other items that require consideration when using this technique are:
  - FOD in x-ray
  - X-ray exposure effects
  - Digitization errors (afterglow, improper digitization hardware, etc.)
  - Data interpretation errors
  - X-ray characteristic curve effects

Summary

Summary

- This package provides a base level description of a new technique which can be used to estimate a parts change in thickness through the use of an x-ray and digital analysis.
- It was shown that digitally analyzing a parts x-ray can identify thickness variation conditions and quantifiably estimate the level of density/grayscale change.
- Using a reference standard of known thickness within the same x-ray as a part provides a means of estimating thickness variation from changes in x-ray density/grayscale.
- Furthermore, using a reference standard of known thickness within the same x-ray as a part reduces if not eliminates the effects of x-ray variation.
- Since ASTM requirements require the use of a penetrameter (reference standard) in each x-ray, the penetrameter is readily available as a tool to use to estimate the relationship between Thickness and Grayscale in parts already x-rayed.
- It has been shown in this package and witnessed numerous times in use that using a reference standard with a thru density lower (thickness higher) than that of the part area in question always yields an accurate if not conservative Thickness to Grayscale relationship.
- For future use of this technique various new reference standards can be developed to better estimate the relationship of an x-rays characteristic curve.
- With adequate process control this technique can be automated global scale to map out part thicknesses in an assembly line and to control quality.